

# Recent Results in Bottomonium

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**Key Words** Quarkonium, quantum chromodynamics, bottomonium, spectroscopy

**Abstract** Great strides have been made in the understanding of bound states of a bottom quark  $b$  and its antiquark  $\bar{b}$  since the discovery of the first  $\Upsilon$  resonances in 1977. These *bottomonium* bound states have a rich spectrum whose masses and transition amplitudes shed valuable light on the strong interactions. The present article reviews some recent developments in bottomonium physics. These include the discovery of the spin-singlet states  $\eta_b(1S, 2S)$  and  $h_b(1P, 2P)$ , the first D-wave states, one or more candidates for spin-triplet  $\chi_{bJ}(3P)$  excitations, and above-threshold states with strong transitions to states below threshold. Information on transitions, production, and signatures of new physics is also presented.

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## 1 INTRODUCTION

### 1.1 $\Upsilon(1S, 2S, 3S?)$ discovery and similarity to charmonium

The first evidence for *bottomonium*, the bound states of a bottom quark  $b$  and the corresponding antiquark  $\bar{b}$ , was seen in the spectrum of  $\mu^+\mu^-$  pairs produced in 400 GeV proton-nucleus collisions at Fermilab (1,2). Evidence was presented for the  $\Upsilon(1S)$  and  $\Upsilon(2S)$  at 9.46 and 10.02 GeV/ $c^2$ , with a hint of a higher-mass state now understood to be the  $\Upsilon(3S)$  at 10.35 GeV/ $c^2$ .

The spacing between 1S, 2S, and 3S levels of bottomonium resembles that in charmonium, suggesting a simple inter-quark potential  $V(r) = C \log(r/r_0)$  (3,4) interpolating between the short-distance  $1/r$  and long-distance  $r$  behaviors expected in quantum chromodynamics (QCD) (5,6,7). Many successful predictions of bottomonium properties followed from such QCD-inspired potentials.

### 1.2 $\Upsilon(nS)$ are bound states of $b$ and $\bar{b}$

The  $\Upsilon(nS)$  states were immediate candidates for members of a new system of quark-antiquark bound pairs, but the charge of the new quark was not yet established. Several years earlier Kobayashi and Maskawa (8) had proposed a six-quark model with doublets  $(u, d)$ ,  $(c, s)$ , and  $(t, b)$  to explain CP violation. The  $u$  (up),

$d$  (down),  $c$  (charm), and  $s$  (strange) quarks were already known in 1977, but the new quark could be either  $t$  (top) or  $b$  bottom. The measurement of the decay rates into lepton pairs of the two lowest-lying states  $\Upsilon(1S)$  and  $\Upsilon(2S)$  at the electron-positron collider DORIS in Germany (9) established the magnitude of the charge of the new quark as  $1/3$  (10), solidifying its role as the  $b$ . It took 17 more years for the top quark to be identified at the Fermilab Tevatron (11,12).

### 1.3 Major players: Fermilab, DORIS, Cornell, Belle, BABAR, ...

A number of laboratories have played a role in the study of bottomonium. Following the discoveries in 1977 at the Fermilab fixed-target experiment E288 (1,2), the electron-positron colliders DORIS (at DESY in Hamburg) and CESR (at Cornell University) made key measurements of the properties of  $b\bar{b}$  states. For two reviews of the early history of these measurements see Refs. (13) and (14); for a history of CESR and its main particle detector CLEO see (15). Subsequently major contributions were made by experiments at the asymmetric electron-positron colliders PEP-II (BABAR Detector) and KEK-B (Belle Detector), the CDF and D0 detectors at the Fermilab Tevatron proton-antiproton collider, and the ATLAS, CMS, and LHCb detectors at the CERN Large Hadron Collider (LHC). One review of the second two decades of bottomonium spectroscopy is Ref. (16). For a more recent and comprehensive survey of quarkonium results see Ref. (17).

## 2 SPECTROSCOPY

### 2.1 Overview: masses, spins, and parities of known states

In Fig. 1 we display the current state of knowledge about bottomonium states and transitions among them. Such states must decay either via  $b\bar{b}$  annihilation

or through transitions to lower bottomonium states, with typical total widths in the tens to hundreds of keV. States above flavor threshold can decay to pairs of flavored mesons and have typical total widths larger by at least two orders of magnitude.

Quark-antiquark composites with total spin  $S = 0, 1$  and orbital angular momentum  $L$  have parity and charge-conjugation eigenvalues  $P = (-1)^{L+1}$  and  $C = (-1)^{L+S}$ . We use the notation S, P, D, ... for states with  $L = 0, 1, 2, \dots$ , with a superscript prefix denoting the spin multiplicity  $2S+1$  and a subscript denoting total angular momentum  $J$ . An integer preceding the angular momentum letter denotes the radial quantum number  $n = 1, 2, \dots$ . Thus, the full notation for the  $\Upsilon(1S)$  is  $1^3S_1$ .  $\Upsilon(nS)$  states are easily produced in hadronic interactions and through virtual photons in  $e^+e^-$  collisions.

Before reviewing discoveries of the past few years (in roughly chronological order), we discuss briefly the notation in Fig. 1. The spin-singlet partners ( $^1S_0$ ) of the  $\Upsilon(nS)$  are called  $\eta_b(nS)$ . The first of these was discovered only a few years ago (18,19) and its 2S partner within the past year (20).

Quarkonium  $^3P_J$  states are denoted by  $\chi_J(nP)$ ; those of bottomonium are called  $\chi_{bJ}(nP)$ . The 1P and 2P states were discovered (21,22) in experiments by the CUSB (Columbia University – Stony Brook) Collaboration at the CESR  $e^+e^-$  collider. They may be produced through electric dipole radiative transitions from excited  $\Upsilon(nS)$  states; in turn, they decay via electric dipole transitions to lower  $\Upsilon(nS)$  states. They may also be produced directly in hadronic interactions, as evidenced by the recent observation of the  $\chi_{bJ}(3P)$  states in hadronic collisions at the LHC (23) and the Tevatron (24) and decaying to  $\gamma + \Upsilon(1S, 2S)$ .

Quarkonium  $^1P_1$  states are called  $h(nP)$ . The charmonium state  $h_c(1P)$  was

the last  $c\bar{c}$  state to be discovered below charmed meson pair threshold (25,26,27). The corresponding bottomonium state  $h_b(1P)$  and the excited state  $h_b(2P)$  were seen relatively recently (28).

The states in Fig. 1 denoted  $\Upsilon(n^3D)$  are spin-triplets with orbital angular momentum  $L = 2$  and thus have  $J = 1, 2, 3$ . Evidence for them will now be discussed.

## 2.2 D-wave states(s): CUSB, CLEO, BABAR

Quarkonium potential models (e.g., (29)) predict masses of  $\Upsilon(1D)$  and  $\Upsilon(2D)$  states within a narrow range around 10.16 and 10.44 MeV (30). An early search for transitions  $\Upsilon(3S) \rightarrow \gamma_1 \chi_{bJ}(2P) \rightarrow \gamma_1 \gamma_2 \Upsilon(1D) \rightarrow \gamma_1 \gamma_2 \gamma_3 \chi_{bJ}(1P) [\rightarrow \gamma_1 \gamma_2 \gamma_3 \gamma_4 \Upsilon(1S)]$  by the CUSB Collaboration found no evidence for the  $\Upsilon(1D)$  states (31). However, with larger statistics and an excellent CsI electromagnetic calorimeter, the CLEO Collaboration was able to identify events with four photons corresponding to the above cascades (32).

The dominant contribution to this chain is predicted to come from  $\Upsilon(1^3D_2)$  (29,30). Under this assumption, the mass of the new state is  $M[\Upsilon(1^3D_2)] = (10.161.1 \pm 0.6 \pm 1.6)$  MeV. The mass is consistent with potential model calculations, as is the product branching fraction (assuming  $J = 2$ ) for the above four transitions followed by  $\Upsilon(1S) \rightarrow e^+e^-$  or  $\mu^+\mu^-$ :  $\mathcal{B} = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}$ . More recently, the BABAR Collaboration (33) has measured the mass of the  $\Upsilon(1^3D_2)$  state using its decay to  $\pi^+\pi^-\Upsilon(1S)$  to be  $M[\Upsilon(1^3D_2)] = (10164.5 \pm 0.8 \pm 0.5)$  MeV/ $c^2$ , also finding weak evidence for the  $J = 1$  and  $J = 3$  states. The angular distributions are consistent with expectations for the  $J = 2$  state.

### 2.3 $\eta_b(1S)$ discovery; splitting from $\Upsilon(1S)$

The ground state of bottomonium,  $\eta_b(1S)$ , was predicted by a variety of QCD-inspired potential models to lie between 35 and 100 MeV below the  $\Upsilon(1S)$  (34). The large range of predictions arose to a great extent from uncertainties in relativistic corrections and in evaluation of the square of the wave function at the origin, entering into the prediction of the hyperfine splitting.

The (allowed) magnetic dipole (M1) transition  $\Upsilon(1S) \rightarrow \gamma\eta_b(1S)$  leads to a very soft photon which is difficult to distinguish from the many photons due to  $\Upsilon(1S) \rightarrow \pi^0 X \rightarrow \gamma\gamma X$ . This led to the attempt to observe the much more energetic photon in  $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$  (911 MeV for  $M[\eta_b(1S)] = 9.4 \text{ GeV}/c^2$ ). The CLEO Collaboration searched for for this transition in 5.9 million  $\Upsilon(3S)$  decays, finding only an upper limit on the rate (35). With  $(109 \pm 1)$  million  $\Upsilon(3S)$  decays, the BABAR Collaboration observed a state lying  $71_{-2.3}^{+3.1}(\text{stat}) \pm 2.7(\text{syst})$  MeV below the  $\Upsilon(1S)$ , while observation of the transition  $\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$  led to a hyperfine splitting of  $(66.1_{-4.8}^{+4.9} \pm 2.0)$  MeV.

The BABAR discovery employed subtraction of substantial backgrounds at lower photon energies. At the  $\Upsilon(3S)$ , initial state radiation (ISR) to  $\Upsilon(1S)$  results in a photon energy of 856 MeV, while radiative transitions to the  $\chi_{bJ}(2P)$  states followed by  $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$  lead to a broad cluster of Doppler-broadened lines around 764 MeV. Using this technique the CLEO Collaboration was able to identify the  $\Upsilon(3S) \rightarrow \gamma\Upsilon(1S)$  transition photon (19), measuring the hyperfine splitting from  $\Upsilon(1S)$  to be  $(68.5 \pm 6.6 \pm 2.0)$  MeV. A more recent measurement of  $M[\eta_b(1S)]$  by the Belle Collaboration using a different technique (described below) gives a slightly smaller hyperfine splitting of  $(57.9 \pm 1.5 \pm 1.8)$  MeV (20), in agreement with the most recent calculations based on lattice QCD (36,37).

## 2.4 Discovery of $h_b(1P)$ , $h_b(2P)$ , and $\eta_b(2S)$

The spin-singlet P-wave states of quarkonium are expected to lie very close in mass to the spin-weighted average of the triplet states, as the hyperfine splitting in leading non-relativistic order is proportional to the square of the wave function at the origin, which vanishes for P-wave states. Such was found to be the case for charmonium (25, 26, 27, 38).

Evidence for the lowest  $^1P_1$  state of bottomonium,  $h_b(1P)$ , was first noted by the BABAR Collaboration (39) in the transition  $\Upsilon(3S) \rightarrow \pi^0 h_b(1P) \rightarrow \pi^0 \gamma \eta_b(1S)$ . The first significant signal for this state, however, came from an unexpected quarter: hadronic transitions to  $h_b(nP)$  from the  $\Upsilon(5S)$ , a bottomonium state lying well above the open flavor threshold.

Two observations prompted the search for  $h_b(nP)$  in such an unlikely process. The CLEO Collaboration had observed the production of  $h_c$  in  $e^+e^- \rightarrow \pi^+\pi^-h_c$  at a center-of-mass energy of 4.16 GeV, lying above charm threshold, at a rate comparable to that for  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  (40). This was a surprise as it indicated none of the expected suppression for a  $c$ -quark spin-flip process. Meanwhile, the Belle Collaboration had observed anomalously high rates for  $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$  at energies above bottom-meson pair production threshold (the dashed horizontal line in Fig. 1) (41). These curious enhancements stimulated a search for  $e^+e^- \rightarrow \pi^+\pi^-h_b$  near the  $\Upsilon(5S)$  ( $M = 10865 \text{ MeV}/c^2$ ) resonance (28).

The search succeeded beyond expectations. Not only was the  $h_b(1P)$  seen, very close to the expected spin-weighted average  $\overline{M}[\chi_{bJ}(1P)]$ , but the  $h_b(2P)$  was observed with even greater significance, near  $\overline{M}[\chi_{bJ}(2P)]$  (see Fig. 1). Belle observed these states in the recoil mass spectrum against  $\pi^+\pi^-$ . In Fig. 2 are shown the Belle observations of dipion transitions from  $\Upsilon(5S)$  to all three



sub-threshold  $\Upsilon(nS)$  states, dipion transitions ( $\Upsilon(2S, 3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ ) from  $\Upsilon(2S, 3S)$  produced via ISR, direct  $\pi^+\pi^-$  transitions to  $h_b(1P, 2P)$  and evidence for a  $\pi^+\pi^-$  transition to  $\Upsilon(1D)$ . These results were updated in Ref. (20), leading to  $M[h_b(1P)] = (9899.1 \pm 0.4 \pm 1.0) \text{ MeV}/c^2$ , which is  $(0.8 \pm 1.1) \text{ MeV}/c^2$  below  $\overline{M}[\chi_{bJ}(1P)]$ , and  $M[h_b(2P)] = (10259.8 \pm 0.5 \pm 1.1) \text{ MeV}/c^2$ , which is  $(0.5 \pm 1.2) \text{ MeV}/c^2$  below  $\overline{M}[\chi_{bJ}(2P)]$ . Thus, no evidence was found for hyperfine splittings in the P-wave bottomonium states.

The Belle Collaboration also was able to observe the transitions  $h_b(1P) \rightarrow \gamma\eta_b(1S)$ ,  $h_b(2P) \rightarrow \gamma\eta_b(1S)$ , and  $h_b(2P) \rightarrow \gamma\eta_b(2S)$  (20). With this they discovered a new state,  $\eta_b(2S)$  with  $M[\eta_b(2S)] = (9999.0 \pm 3.5_{-1.9}^{+2.8}) \text{ MeV}/c^2$ , and made the world's most precise measurement of  $M[\eta_b(1S)] = (9402.4 \pm 1.5 \pm 1.8) \text{ MeV}/c^2$ . Additional evidence for the  $\eta_b(2S)$  was obtained in a study (42) using CLEO data, resulting in a substantially lower mass  $M[\eta_b(2S)] = (9974.6 \pm 2.3 \pm 2.1) \text{ MeV}/c^2$ , and, in addition, a mass measurement of  $\eta_b(1S)$ :  $M[\eta_b(1S)] = (9393.2 \pm 2.3 \pm 2.1) \text{ MeV}/c^2$  based on  $3\sigma$  evidence for  $\Upsilon(1S) \rightarrow \gamma\eta_b(1S)$ .

## 2.5 The $\chi_{bJ}(3P)$ states

Some bottomonium states, though expected to lie below  $B\bar{B}$  flavor threshold and thus expected to be narrow, are high enough in mass that they cannot be reached by one or more electric dipole transitions from a higher-lying  $\Upsilon(nS)$  state also lying below flavor threshold. They are thus difficult to observe in  $e^+e^-$  collisions. The  $\chi_{bJ}(3P)$  states are one example. Most bottomonium potential models predict them to lie below flavor threshold; a representative set of masses (29) is  $M[\chi_{b0}(3P)] = 10500.7 \text{ MeV}/c^2$ ,  $M[\chi_{b1}(3P)] = 10516.0 \text{ MeV}/c^2$ , and  $M[\chi_{b2}(3P)] = 10526.4 \text{ MeV}/c^2$ , to be compared with  $2M(B) \simeq 10560 \text{ MeV}/c^2$ .

Other models predict values within ten or twenty  $\text{MeV}/c^2$  of these [see, e.g., (43, 44)].

The  $\chi_{bJ}(3P)$  states can be produced in hadronic interactions, for example through two-gluon fusion (see Sec. 4.3), and then can be observed through their electric dipole transitions to lower  $\Upsilon(nS)$  states. In this manner the ATLAS Collaboration (23) reported observing not only the previously known decays  $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$  and  $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S, 2S)$ , but also  $\chi_{bJ}(3P) \rightarrow \gamma\Upsilon(1S, 2S)$ .

Using converted photons (with superior energy resolution), the ATLAS Collaboration measures the weighted average of the masses contributing to these last two transitions to be  $\bar{m}_3 = 10530 \pm 5 \pm 9 \text{ MeV}$ . It is most likely that this receives little contribution from the  $\chi_{b0}(3P)$ , whose partial width to hadronic states is expected to be considerably larger than that of the other two states (29), so it is probably to be compared with some weighted combination of the predicted masses of  $\chi_{b1}(3P)$  and  $\chi_{b2}(3P)$ .

The D0 Collaboration also has observed a similar structure, using converted photons (24). Calibrating their energy using the known transitions involving the  $\chi_{bJ}(1P, 2P)$  states, they find  $\bar{m}_3 = 10551 \pm 14 \pm 17 \text{ MeV}/c^2$ .

## 2.6 Above-threshold (molecular?) states

For years, a puzzle in the quark model was why all the observed hadrons appeared to be composed either of quark-antiquark (mesons) or three quarks (baryons). These configurations can exist in color singlets, but they are not the only ones. What about tetraquarks ( $qq\bar{q}\bar{q}$ ), pentaquarks ( $qqqq\bar{q}$ ) or more complicated objects? After all, nuclei do exist, though principally they are thought of as clusters of baryons.

Since the earliest days of hadron spectroscopy, it was recognized that properties of levels can be strongly influenced by nearby channels. An early example was the resonance  $\Lambda(1405)$ , decaying to  $\Sigma\pi$  but strongly influenced by the  $\bar{K}N$  threshold lying just above it (45). Another example is the  $f_0(980)$ , decaying to  $\pi\pi$  but behaving remarkably like a  $K\bar{K}$  bound state or “molecule” (46). The description of such states requires one to go beyond a simple  $qqq$  or  $q\bar{q}$  picture.

Molecular “charmonium” was proposed soon after the discovery of charm (47, 48). The attraction of a charmed meson  $D = c\bar{q}$  and an anticharmed meson  $\bar{D} = \bar{c}q'$  could be viewed as a molecular force mediated by the light quarks with the  $c$  and  $\bar{c}$  acting as spectators. An excellent candidate for such a state was identified in 2003 by the Belle Collaboration (49): the  $X(3872)$ , originally seen decaying to  $\pi^+\pi^-J/\psi$ . [For a detailed description of this and related states see Ref. (50).] Its mass is very close to  $M(D^0) + M(D^{*0})$ . The consensus is that it shares many properties of a  $D^0\bar{D}^{*0}$  molecule, with some admixture of a  $^3P_1$  charmonium state to explain its observed decay to  $\gamma J/\psi$ .

It now appears that there are candidates for molecular bottomonium as well. The surprisingly large rates for transitions from  $\Upsilon(5S, 10865)$  to  $\pi^+\pi^-\Upsilon(1S, 2S, 3S)$  and  $\pi^+\pi^-h_b(1P, 2P)$  appear largely to be due to a sequential process in which a pion and a  $B\bar{B}^*$ ,  $B^*\bar{B}$ , or  $B^*\bar{B}^*$  are first produced, forming resonances which then emit another pion to reach the final state (51). These bottomonium-related states are electrically charged, and have come to be called  $Z_b(10610)$  and  $Z_b(10650)$ .

Their large mass, indicating the presence of two bottom quarks in their composition, together with their possession of electrical charge, marks these states as necessarily unconventional. Their proximity to the  $BB^*$  and  $B^*B^*$  thresholds at  $M(B) + M(B^*) = 10604.6 \text{ MeV}/c^2$  and  $2M(B^*) = 10650.2 \text{ MeV}/c^2$  makes

their identification as molecular states an attractive possibility (52). Their parity is positive as would be expected for S-wave molecular states. Their participation in the intermediate state of the transitions from the  $\Upsilon(5S)$  which produce  $h_b(1P, 2P)$  as strongly as  $\Upsilon(1S, 2S, 3S)$  follows naturally from a careful accounting of the ratio of  $b\bar{b}$  triplet and singlet in their wave functions. The molecular description of these states predicts equal total widths (as observed) and several other decay modes such as  $\eta_b(1S)\rho$ . The properties of these states are summarized in Table 1. Both have isospin  $I = 1$ , positive G-parity, and are determined to have spin-parity  $J^P = 1^+$  by angular analysis of their production and decay kinematics.

On the basis of these properties, one might additionally expect the existence of neutral partners to these charged  $Z_b$  states. The Belle Collaboration has recently announced evidence at a significance of  $4.9\sigma$  for such a state at a mass of  $10609^{+8}_{-6} \pm 6 \text{ MeV}/c^2$  in  $\pi^0\pi^0$  transitions from  $\Upsilon(5S)$  (53). The evidence for a neutral state corresponding to the  $Z_b(10650)$  in the same analysis is insignificant.

Finally, the Belle Collaboration has recently announced the results of their investigation of three-body decays of  $\Upsilon(5S)$  to final states of  $[B^{(*)}B^{(*)}]^{\pm}\pi^{\mp}$  (54). In this study it was observed that the  $Z_b(10610)$  decays dominantly  $(86.0 \pm 3.6)\%$  of the time to  $BB^*$ , while the  $Z_b(10650)$  decays dominantly  $(73.4 \pm 7.0)\%$  to  $B^*B^*$ , which serves as additional evidence in favor of the molecular interpretations of the charged  $Z_b$  states.

## 2.7 The $Y_b(10890)$

As noted in Sec. 2.4, in 2008, the Belle Collaboration observed anomalously large rates (up to two orders of magnitude larger than expected) for the processes

$\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)$  if the  $\Upsilon(5S)$  is interpreted as the fourth radial excitation of the  $1^{--} \Upsilon(1S)$  state (41). (See discussion later in Sec. 3.6.5.) This led them to conduct a careful scan of the cross section for  $\pi^+\pi^-\Upsilon(nS)$  in the vicinity of the known mass of the  $\Upsilon(5S)$ , 10865 GeV/ $c^2$ , taking data at center of mass energies between 10.83 and 11.02 GeV. In this study, they observed a peak in  $\sigma(e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-)$  ( $n = 1, 2, 3$ ) at an energy of  $(10888_{-2.6}^{+2.7} \pm 1.2)$  MeV with a width of  $(30.7_{-7.0}^{+8.3} \pm 3.1)$  MeV (55), as will be discussed in more detail in Sec. 3.6.5. The BABAR Collaboration also recently measured two peaks in the  $e^+e^- \rightarrow b\bar{b}$  cross section, one at  $(10876 \pm 2)$  MeV with width  $(43 \pm 4)$  MeV and the other at  $(10996 \pm 2)$  MeV with width  $(37 \pm 3)$  MeV (56).

The displacement of the peak measured in  $\Upsilon(nS)\pi^+\pi^-$  by Belle and the lower BABAR peak measured in  $b\bar{b}$  decays has led to the suggestion that these peaks may not, in fact, be the  $\Upsilon(5S)$  but rather some exotic state (57).

## 2.8 Special aspects of $\Upsilon(5S)$

Both  $B\bar{B}^*$  and  $B^*\bar{B}$  can interact by exchanging pions, while in order to do so  $B\bar{B}$  states have to undergo virtual transitions to  $B^*\bar{B}^*$ . This may explain the existence of the “molecular” states  $Z_b(10610)$  and  $Z_b(10650)$ , with the  $\Upsilon(4S)$  behaving more as a conventional  $b\bar{b}$  level. (See, however, the discussion below of hadronic transitions of  $\Upsilon(4S)$ .)

As the  $Z_b$  states have isospin  $I = 1$ , they must be produced in  $e^+e^-$  collisions in association with a pion. The first  $\Upsilon$  resonance which permits this is the  $\Upsilon(5S)$ , at 10865 MeV. This could explain why the beautiful proliferation of states in  $\Upsilon(5S)$  decays is not seen at lower energies.

## 2.9 Theoretical successes and shortcomings

Potential models based on short-distance gluon exchange and a linear  $b\bar{b}$  confining potential at large distances have reproduced reasonably well the spin-triplet  $nS$ ,  $nP$ , and  $1D$  bottomonium spectra below flavor threshold. Pioneering work in this area (5, 6, 7) has been extended to include the effects of relativistic corrections (see, e.g., (58)) and the effects of coupling to open channels (see, e.g., many references in (17)). Potential model predictions for the masses of the  $1D$  and  $3P$  levels had a narrow range of ten or twenty MeV and were verified within that range. For the lowest-lying levels, lattice gauge theories (extended to include the effects of light-quark pairs) have also provided an effective description (see, e.g., (59)).

One prediction of spin-dependent effects, shared in many approaches, also had great success. This is the small value of the hyperfine splitting in  $1P$  and  $2P$   $b\bar{b}$  states, as confirmed by the  $h_b(1P)$  and  $h_b(2P)$  masses (51). This may be traced to the vanishing of the P-wave wave function at the origin. The hyperfine splitting in  $nS$  states posed more of a problem for potential models, with a wide range of predictions (34). Recent estimates of  $M[\Upsilon(1S)] - M[\eta_b(1S)]$  based on lattice gauge theory (36, 37) have been fairly close to the observed values.

The situation is quite different for states above flavor threshold. As exemplified by the states  $Z_b(10610)$  and  $Z_b(10650)$ , a  $b\bar{b}$  description of such states does not suffice. They lie just a few MeV below  $M(B) + M(B^*)$  and  $2M(B^*)$ , respectively, suggesting that these channels play an important role in their makeup. Indeed, successful predictions result from regarding these as molecular bottomonium states (52). The discovery of these unique resonances is simply the most recent in a series of observations that underscores the importance of nearby thresh-

olds in spectroscopy (6, 7, 57, 60, 61, 62).

### 3 TRANSITIONS

#### 3.1 Decays of $\Upsilon(1S)$ to light-quark states

The  $\Upsilon(1S)$  is expected to decay mainly  $[(81.7 \pm 0.7)\%]$  via three gluons, with  $(2.2 \pm 0.6)\%$  to two gluons and a photon (63). The two- and three-gluon channels provide an entry to many potential final states, including states made of pure glue (glueballs), light Higgs bosons, and states made of lighter quarks. However, until recently relatively few of these had been identified, in contrast to the wealth of final states seen in  $J/\psi$  decays. (One interesting branching fraction is  $\mathcal{B}[\Upsilon(1S) \rightarrow \eta'(958) + X] = (2.94 \pm 0.24)\%$  (63).)

This situation changed with the publication of observations by Belle of several exclusive hadronic decays of  $\Upsilon(2S)$  and  $\Upsilon(1S)$  (64), and by CLEO of seventy-three exclusive hadronic decay modes of  $\Upsilon(1S)$  and seventeen of  $\Upsilon(2S)$  (65). The branching fractions for these decays ranged from  $0.5 \times 10^{-6}$  to  $110 \times 10^{-5}$ . Together with multi-particle decays of  $\chi_{bJ}(1P, 2P)$  to be mentioned below, such results pave the way for a more complete understanding of how multi-gluon final states fragment into hadrons.

#### 3.2 Decays of $\Upsilon(1S)$ to charm, charmonium

The mechanism of hadronic quarkonium production still remains obscure nearly four decades after the discovery of the  $J$  in proton-beryllium collisions. The inclusive decays of bottomonium states to charmonium can help to illuminate this mechanism by providing a clean gluonic initial state.

The CLEO Collaboration studied the processes  $\Upsilon(1S) \rightarrow J/\psi X$ ,  $\psi(2S)X$ ,

$\chi_{b1}(1P)X$ ,  $\chi_{b2}(1P)X$  using 21 million  $\Upsilon(1S)$  decays (66). These measurements can test the *color octet model* (67), in which a substantial fraction of hadronic quarkonium production proceeds through a color-octet component of the quarkonium wave function. What is found is that the ratios of the excited charmonium states mentioned above to  $J/\psi X$  production are about a factor of two larger than predicted by the color-octet model (68). The BABAR Collaboration studied the  $\Upsilon(1S) \rightarrow D^{*\pm}(2010)X$  decays (69) as a function of the scaled  $D^{*\pm}$  momentum, finding the color-octet contribution to be disfavored (70).

### 3.3 Multi-particle decays of $\chi_{bJ}(1P, 2P)$

The decays of heavy quarkonia into states of light-quark hadrons can tell us how initial parton states consisting of gluons and quarks turn into observable particles. Many Monte Carlo programs make assumptions about this process which have not been fully tested against data. The CLEO Collaboration studied the decays of the  $\chi_{bJ}(1P)$  and  $\chi_{bJ}(2P)$  states into 659 different states of pions, kaons,  $\eta$ s, and baryons (71), identifying 14 modes with significant signals. The greatest significance was found for signals from the  $J = 1$  states. The selection criteria were limited to those final states containing 12 or fewer particles, where a  $\pi^0 \rightarrow \gamma\gamma$  or a  $K_S \rightarrow \pi^+\pi^-$  counts for two. Even with this high multiplicity it appeared that significant higher multiplicities were being missed.

### 3.4 Electric dipole transitions $S \leftrightarrow P \leftrightarrow D$

The transitions  $\Upsilon(nS) \leftrightarrow \chi_b(mP) \leftrightarrow \Upsilon(kD)$  can occur via single electric dipole photon emission or absorption. They occur with observable branching fractions for the narrow bottomonium states below flavor threshold. For spin-triplet states,



they have been seen in  $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$ ,  $\Upsilon(2S) \rightarrow \gamma\chi_{bJ}(1P)$ ,  $\Upsilon(1D) \rightarrow \gamma\chi_{bJ}(1P)$ ,  $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S, 2S, 1D)$ , and  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(1P, 2P)$ . More recently they have also been seen in the spin-singlet states:  $h_b(1P) \rightarrow \gamma\eta_b(1S)$  and  $h_b(2P) \rightarrow \gamma\eta_b(1S, 2S)$ . These transitions satisfy  $\Delta L = 1$  with change of parity and no change in quark spin. They involve the matrix element of  $\vec{r}$  between initial- and final-state wave functions. Their rates are given by expressions quoted (e.g.) in Refs. (7, 29). They are illustrated in Fig. 1.

Transitions  $nP \rightarrow nS$  or  $nD \rightarrow nP$  involve initial and final wave functions with the same number of nodes and have substantial dipole matrix elements. Although the number of nodes in the wave functions differs for  $nP$  and  $[n-1]S$  or  $nS$  and  $[n-1]P$ , the corresponding dipole matrix elements are also appreciable. These are the transitions that would be allowed in the three-dimensional harmonic oscillator. On the other hand, the transitions  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(1P)$  are highly suppressed; in a three-d harmonic oscillator they would be forbidden. This suppression holds for a wide range of power-law potentials (72). As a result, dipole matrix elements for these transitions are particularly sensitive to relativistic corrections, providing a way of discriminating among various approaches.

### 3.5 Forbidden M1: $\Upsilon(2S, 3S) \rightarrow \gamma\eta_b(1S)$

The nonrelativistic approximation for magnetic dipole transition rates in  $Q\bar{Q}$  bound states (34) is

$$\Gamma(^3S_1 \rightarrow \gamma^1S_0) = \frac{4}{3}\alpha\frac{e_Q^2}{m_Q^2}I^2k^2, \quad (1)$$

where  $\alpha$  is the fine-structure constant,  $e_Q$  is the quark charge in units of  $|e|$ ,  $m_Q$  is the quark mass, and  $k$  is the magnitude of the photon three-momentum in the rest frame of the decaying particle. The overlap integral  $I$  is defined by

$I = \langle f | j_0(kr/2) | i \rangle$ , where  $j_0(kr/2) = \sin(kr/2)/(kr/2) \simeq 1 - (kr)^2/24 + \dots$

When the initial and final states have the same principal quantum numbers, and the photon energy is low, the overlap integral is close to unity. However, when the initial and final principal quantum numbers are not the same, a *forbidden* transition, the leading matrix element vanishes as a result of the orthogonality of the initial and final wave functions. Consequently, the overlap integral becomes proportional to  $k^2$ . The  $\eta_b$ , discussed earlier, was first detected in the forbidden transition  $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$  by the BABAR Collaboration (18). It was then seen by BABAR in the transition  $\Upsilon(2S) \rightarrow \gamma\eta_b(1S)$  (73) and confirmed in  $\Upsilon(3S) \rightarrow \gamma\eta_b(1S)$  by CLEO (19). These measurements are compared in Table 2.

The masses measured in these transitions are to be compared with that measured by Belle (20) in the allowed E1 transitions  $h_b(1P, 2P) \rightarrow \gamma\eta_b(1S)$ :  $M[\eta_b(1S)] = (9402.4 \pm 1.5 \pm 1.8) \text{ MeV}/c^2$ . (This experiment also measured  $\Gamma[\eta_b(1S)] = (10.8^{+4.0+4.5}_{-3.7-2.0}) \text{ MeV}/c^2$ .) This last mass is free from potential distortion of the spectral shape that occurs in the forbidden M1 transitions due to the  $k^2$  dependence of the overlap integral  $I$ . (See the discussion concerning the sensitivity of the determination of mass of the  $\eta_c$  produced in M1 decays of  $J/\psi, \psi'$  in Ref. (74).) It also agrees better with recent lattice calculations (36, 37). The branching fractions are consistent with some but not all of the wide range of predictions (34).

### 3.6 Hadronic $b\bar{b}' \rightarrow b\bar{b} + X$

Hadronic transitions of heavy quarkonia provide unique insights into the nature of hadronization at low momentum transfer, and are generally successfully described in terms of multipole moments of the QCD field (75, 76, 77). Two-pion transitions were the only hadronic transitions known in the system until the obser-

vation by the CLEO Collaboration of an unexpectedly large rate for the transition  $\chi_{b1,2}(2P) \rightarrow \omega \Upsilon(1S)$  published in 2004 (78). Since then, updated measurements of the previously known dipion transitions have been made (79, 80, 81, 82), and, additionally, a wide array of new transitions have been investigated by CLEO, Belle and BABAR :  $\chi_{bJ}(2P) \rightarrow \pi\pi\chi_{bJ}(1P)$  (83, 81),  $\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$  (84, 82, 85), and both  $\pi\pi$  and  $\eta$  transitions from states above the open beauty threshold,  $\Upsilon(4S, 5S)$  to states below threshold ( $\Upsilon(1S, 2S, 3S)$ ) (86, 87, 41).

Measurement of the relative rates for various hadronic transitions, together with invariant mass and angular distributions, particularly for those transitions mediated by different terms in the multipole expansion, can be particularly enlightening for our understanding of hadronization. The past decade has seen substantial advances in the study of hadronic transitions in the bottomonium spectrum as the following discussion shows.

**3.6.1 PROGRESS IN  $\Upsilon(nS) \rightarrow \pi\pi\Upsilon(mS)$**  Among the more interesting questions concerning dipion transitions between  $\Upsilon(nS)$  states below open beauty threshold arose from the stark contrast between the invariant mass distributions of the pion pair for the transition  $\Upsilon(3S) \rightarrow \pi\pi\Upsilon(1S)$  as compared to that for  $\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$ . The  $\pi\pi$  invariant mass distribution in the latter transition agrees well with that from the analogous transition  $\psi(2S) \rightarrow \pi\pi J/\psi$ , while the former transition has a double-humped invariant mass structure. While the  $2S \rightarrow 1S$  transitions can be explained by a fairly simple matrix element, the  $\Upsilon(3S) \rightarrow \Upsilon(1S)$  distribution cannot.

The CLEO Collaboration studied the decay dynamics of  $(\Upsilon(3S, 2S)) \rightarrow \pi\pi(\Upsilon(2S, 1S))$  using a sample of  $4.98 \times 10^6$   $\Upsilon(3S)$  (79). The size of this data sample enabled at last a detailed study of the decay dynamics, which was done according to the

formalism of Brown and Cahn (88) and the multipole expansion model cited previously. In addition, the branching fractions for all  $\Upsilon(nS) \rightarrow \pi\pi\Upsilon(mS)$  have been updated, first by CLEO (80), and more recently by BABAR (81, 82). Two of these branching fractions,  $\mathcal{B}(\Upsilon(2S, 3S)) \rightarrow \pi\pi\Upsilon(1S)$ , are now known to a relative uncertainty of less than 1.5% (63) and therefore can be more profitably used as tagging modes for searches for unusual decays of  $\Upsilon(1S)$  (see Section 5).

**3.6.2  $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$**  As noted previously, the observation by the CLEO Collaboration of  $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S) (J = 1, 2)$  (78) represented the first observation of any non- $\pi\pi$  hadronic transition between bottomonium states, and also the first observation of  $\chi_{bJ}(2P)$  in something other than an E1 radiative transition. The analysis involved a full reconstruction of the decay chain  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$ ;  $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$ ;  $\Upsilon(1S) \rightarrow \ell^+\ell^- (\ell \equiv e, \mu)$  using the full  $\Upsilon(3S)$  CLEO data sample of  $5.9 \times 10^6 \Upsilon(3S)$  decays. The resulting nearly background-free analysis revealed branching fractions of  $(1.63_{-0.31}^{+0.35} \pm 0.16) \%$  and  $(1.10_{-0.28}^{+0.32} \pm 0.11) \%$  for the  $\chi_{b1}(2P)$  and  $\chi_{b2}(2P)$  transitions, respectively.

The  $\chi_{bJ}(2P) \rightarrow \omega\Upsilon(1S)$  process is expected to proceed via the emission of three E1 gluons (89), since the quantum numbers of the  $\omega$  are that of the photon,  $J^{PC} = 1^{--}$  and the ratio of rates for the  $\chi_{b2}(2P)$  transition to that for the  $\chi_{b1}(2P)$  transition is expected to be  $1.3 \pm 0.3$ . The measured branching fractions for the  $\omega$  transitions from CLEO yield a ratio of rates between 0.9 and 1.5, in agreement with this prediction.

**3.6.3  $\chi_{bJ}(2P) \rightarrow \pi\pi\chi_{bJ}(1P)$**  Dipion transitions are expected to be the dominant transitions between radially excited heavy quarkonium states and their lower-mass partners, as they appear in the lowest possible order in the multipole expansion (77). Transitions from the  $\chi_{bJ}(2P)$  and  $\chi_{bJ}(1P)$  states of the same  $J$

(and in fact the states  $\eta_b(2S)$  and  $\eta_b(1S)$ ) have been long expected, and in 2006, CLEO published the first observation of  $\chi_{bJ}(2P) \rightarrow \pi\pi\chi_{bJ}(1P)$  transitions.

The CLEO analysis (83) utilized the involved a full reconstruction of the decay chain  $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$ ;  $\chi_{bJ}(2P) \rightarrow \pi\pi\chi_{bJ}(1P)$ ;  $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$ ;  $\Upsilon(1S) \rightarrow \ell^+\ell^-$  and again used the full CLEO  $\Upsilon(3S)$  data set. The results from both  $\pi^+\pi^-$  and  $\pi^0\pi^0$  analyses were combined, and branching fractions of  $(6.0 \pm 1.6 \pm 1.4)\%$  and  $(8.6 \pm 2.3 \pm 2.1)\%$ , for  $J = 2$  and  $J = 1$ , respectively (63).

A study by BABAR published in 2011 (81), using a much larger sample of  $\Upsilon(3S)$  decays, obtained precise measurements of the branching fractions:  $\mathcal{B}(\chi_{b1}(2P) \rightarrow \pi^+\pi^-\chi_{b1}(1P)) = (9.2 \pm 0.6 \pm 0.9)\%$  and  $\mathcal{B}(\chi_{b2}(2P) \rightarrow \pi^+\pi^-\chi_{b2}(1P)) = (4.9 \pm 0.4 \pm 0.6)\%$ .

**3.6.4  $\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$  AND SEARCH FOR RELATED TRANSITIONS** The decay  $\psi(2S) \rightarrow \eta J/\psi$  was one of the first hadronic transitions observed in charmonium, with a branching fraction of  $\mathcal{B}[\psi(2S) \rightarrow \eta J/\psi] = (3.28 \pm 0.07)\%$ (63), which is quite large given the tiny available phase space. By contrast, until a few years ago, only an upper limit was known for the corresponding bottomonium process:  $\mathcal{B}[\Upsilon(2S) \rightarrow \eta\Upsilon(1S)] < 2 \times 10^{-3}$  (90).

The production of a pseudoscalar meson in hadronic transitions between two  $^3S_1$  states involves the flip of a heavy quark spin (77,91,92). Such transitions in bottomonium thus can probe the chromomagnetic moment of the  $b$  quark. Their rates are expected to scale as  $\Gamma \propto (p^*)^3/m_Q^4$ , where  $m_Q$  is the mass of the heavy quark  $Q = c, b$ . Then one predicts

$$\frac{\Gamma[\Upsilon(2S, 3S) \rightarrow \eta\Upsilon(1S)]}{\Gamma[\psi(2S) \rightarrow \eta J/\psi]} = (0.0025, 0.0013) , \quad (2)$$

implying  $\mathcal{B}[\Upsilon(2S, 3S) \rightarrow \eta\Upsilon(1S)] = (7.8, 6.4) \times 10^{-4}$  using the latest values from Ref. (63). An explicit potential model calculation (91) obtains similar values:

$(6.9, 5.4) \times 10^{-4}$ .

The transition  $\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$  was first observed by the CLEO Collaboration in about 9 million  $\Upsilon(2S)$  (84). The rate was about a factor of (four,three) below the (scaling,potential) prediction. In just under 100 million  $\Upsilon(2S)$  decays, the BABAR Collaboration essentially confirmed this result (82). More recently, the Belle Collaboration, in 158 million  $\Upsilon(2S)$ , obtained a rate about 50% higher than CLEO's or BABAR's (85). These results are summarized in Table 3, for the transitions  $\Upsilon(2S, 3S) \rightarrow (\eta, \pi^0)\Upsilon(1S, 2S)$ .

The CLEO and Belle upper limits for the isospin-forbidden transition  $\Upsilon(2S) \rightarrow \pi^0$ , and the CLEO limit for  $\Upsilon(3S) \rightarrow \pi^0\Upsilon(1S)$ , can be compared with predictions based on scaling from the ratio of  $\psi(2S) \rightarrow \pi^0 J/\psi$  and  $\psi(2S) \rightarrow \eta J/\psi$ . Updating the calculation in Ref. (84):

$$\frac{\mathcal{B}[\Upsilon(2S, 3S) \rightarrow \pi^0\Upsilon(1S)]}{\mathcal{B}[\Upsilon(2S, 3S) \rightarrow \eta\Upsilon(1S)]} = (15.9 \pm 1.3, 0.41 \pm 0.03)\% . \quad (3)$$

The Belle upper limit  $\mathcal{B}[\Upsilon(2S) \rightarrow \pi^0\Upsilon(1S)] < 0.41 \times 10^{-4}$  is in mild conflict with the first of these values.

**3.6.5  $\Upsilon(4S, 5S) \rightarrow X + \Upsilon(nS)$  [ $X = \pi\pi, \eta$ ]** Because the  $\Upsilon(4S)$  and  $\Upsilon(5S)$  resonances lie above open-bottom threshold, they are much broader than the below-threshold  $\Upsilon(1S, 2S, 3S)$ . Their dominant decays are to those open-bottom mesons whose pair-production threshold lies lower in mass. The large  $\Upsilon(4S, 5S)$  data samples accumulated by BABAR and Belle make possible, despite their small expected branching fractions, the observation of hadronic and radiative transitions from  $\Upsilon(4S)$  and  $\Upsilon(5S)$  — and their observation yields additional interesting and important information concerning the nature of the bottomonium system.

Both BABAR and Belle have studied the transitions  $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)$  using their large  $\Upsilon(4S)$  data samples, exclusively reconstructing the full transi-

tion, with the  $\pi^+\pi^-$  observed in conjunction with the leptonic decay  $\ell^+\ell^- = (e^+e^-, \mu^+\mu^-)$  of the daughter  $\Upsilon(nS)$  state. The partial widths for  $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)$  thus obtained are similar to the partial widths for  $\Upsilon(1S, 2S, 3S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)$  (86, 87). This is what one would have naïvely expected, though the BABAR analysis made an important observation concerning the invariant mass of the  $\pi^+\pi^-$  pairs emitted in the  $\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)$  transition. That is, the distribution of the  $\pi^+\pi^-$  invariant mass in this transition bears a striking resemblance to that of the  $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  transition. Interestingly, both are  $\Delta n = 2$  transitions, while the  $\Delta n = 3$  transitions resemble more closely their  $\Delta n = 1$  counterparts.

By contrast, the transitions  $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  observed by the Belle Collaboration showed significant discrepancies with respect to theoretical expectations. In a sample of  $21.7 \text{ fb}^{-1}$  of  $e^+e^-$  collisions at an energy corresponding to  $M(\Upsilon(5S))$ , Belle observed very large rates for the transitions  $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S, 3S)$ : up to 100 times larger than the corresponding rates for  $\pi^+\pi^-$  transitions among sub-threshold  $\Upsilon(nS)$  states (41). This was so far above the expectations of similar rates that immediately speculation ensued concerning the possible existence of tetraquark or other exotic non- $\Upsilon(nS)$  states near  $\Upsilon(5S)$  (93). Table 4 summarizes the results of the rate measurements for  $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$ , and includes the rates for  $\Upsilon(1S, 2S, 3S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)$  for comparison.

Given the observation of  $\pi^+\pi^-$  transitions from  $\Upsilon(nS)$  states above open-bottom threshold, it might be expected that other hadronic transitions from such states might also be observable. Using their full  $\Upsilon(4S)$  data sample, the BABAR Collaboration has observed the transition  $\Upsilon(4S) \rightarrow \eta\Upsilon(1S)$ , with  $\eta$  decaying to

$\pi^+\pi^-\pi^0$  and the  $\Upsilon(1S)$  decaying leptonically. The reported branching fraction of  $(1.96 \pm 0.11) \times 10^{-4}$  (86) is unexpectedly high — approximately 2.5 times greater than the branching fraction for the dipion transition to  $\Upsilon(1S)$ .

## 4 PRODUCTION

The production of heavy quarkonia in hard-scattering processes involves different momentum scales in both perturbative and nonperturbative regimes of QCD. A detailed understanding of this process is therefore an important test of our understanding of QCD.

A number of different approaches have been proposed to factorize the high-momentum (short-distance) scale process leading to a  $Q\bar{Q}$  pair (predominantly by gluon-gluon fusion diagrams) and the low-momentum (long-distance) scale of the process that binds the  $Q\bar{Q}$  into color singlet quarkonia of the given quantum numbers: the color singlet model (CSM) (94,95,96), NRQCD factorization (97), fragmentation function factorization (98), and  $k_T$  factorization (99,100).

The mutual relations and differences among these approaches are discussed in detail in (17). One of the open issues regards the contribution of  $Q\bar{Q}$  pairs that are in color singlet (CS) as compared to those in which the  $Q\bar{Q}$  pairs are in a color octet (CO). In the QCD-based CSM only the former is considered, while in the NRQCD,  $k_t$  and fragmentation approaches both singlet and octet contributions exist.

The parameters relevant for the calculation of the color singlet contribution can be extracted from measurements of quarkonium decays using potential models or lattice calculations, so the inclusive differential cross section has no additional free parameters. It is not possible at present to relate the parameters of the



color-octet contribution to quantities measured in quarkonium decays, and they are usually determined from fits to differential cross sections.

Bottomonium is heavier and less relativistic than charmonium, so the agreement between theory and experiment is expected to be better for bottomonia. However the cross sections for bottomonia are much smaller, and until the advent of the LHC, most of the measurements of heavy quarkonium hadroproduction involved  $J/\psi$  and  $\psi(2S)$ . Also, experimentally it is more difficult to determine the  $\Upsilon(nS)$  that are directly produced subtracting the contribution originating from the decays of higher resonances, since the spectrum below the open-flavor threshold is much richer compared to that of charmonium.

#### 4.1 Differential cross sections for $\Upsilon(nS)$ vs. theory

One of the key features of the differential cross section for direct  $\Upsilon(nS)$  production is its  $p_t$  dependence. At leading order the color singlet contribution has a  $p_t^{-8}$  dependence, while the color octet contribution has a  $p_t^{-4}$  dependence due to gluon fragmentation. However at NLO the color singlet contribution has large corrections proportional to  $p_t^{-6}$ , and a small correction proportional to  $p_t^{-4}$  due to quark fragmentation. The NNLO corrections have been only partially calculated, but the gluon fragmentation provides large corrections proportional to  $p_t^{-4}$ .

No significant rapidity ( $y$ ) dependence is expected in the central region. In the high  $p_t$  limit the shapes of the differential cross sections are predicted to be the same for all the  $\Upsilon(nS)$ .

For the color singlet contribution the ratios of the  $\Upsilon(nS)/\Upsilon(1S)$  cross sections are simply related to the ratios of wavefunctions at the origin.

The CDF experiment measured the inclusive differential cross section, as a

function of  $p_t$ , for  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$  production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  in the rapidity interval  $|y| < 0.4$  (101). The D0 experiment measured the inclusive differential cross sections for  $\Upsilon(1S)$  and  $\Upsilon(2S)$  in a broader interval,  $|y| < 1.8$  (102).

The  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ , and  $\Upsilon(3S)$  differential cross sections have been measured at LHC in  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$ .

The CMS experiment has measured the differential cross sections as a function of  $p_t$  for  $p_t < 30 \text{ GeV}/c^2$  in the rapidity range  $|y| < 2$  (103). They find that the  $p_t$  dependence of the three cross sections is in excellent agreement with the Tevatron measurements despite the substantial differences in collision energy and  $y$  interval.

The LHCb experiment, whose detectors cover the forward rapidity region, has presented measurements of the double differential cross section as a function of  $p_t$  and  $y$  for  $p_t < 15 \text{ GeV}/c^2$  and  $2.0 < y < 4.5$  (104).

Finally, the ATLAS experiment has recently extended the measurement of these cross sections up to  $p_t < 70 \text{ GeV}/c^2$  in the rapidity range  $|y| < 2.25$  based on an integrated luminosity of  $1.8 \text{ fb}^{-1}$  (105). The measured cross sections are in agreement with the measurements from CMS and LHCb, in the rapidity ranges covered by both experiments.

The measured cross sections are qualitatively in agreement with the various predictions, but ultimately no prediction is able to describe cross sections accurately in all  $p_t$  ranges. The comparison is made more difficult by the uncertainties in the  $\Upsilon(nS)$  polarization, which result in uncertainties in acceptance corrections, and by the uncertainties in the contribution to the inclusive differential cross sections from decays of higher resonances.

The ratios of the  $\Upsilon(2S, 3S)$  to  $\Upsilon(1S)$  cross sections as a function of  $p_t$  have been measured by CMS (103) and ATLAS (105). Both experiments observe an increase for both ratios up to  $p_t \approx 30 \text{ GeV}/c^2$ . At larger  $p_t$ , so far measured only by ATLAS, the cross section ratios seem to reach a saturation. At large  $p_t$  the direct production is expected to dominate over indirect contributions from decays of higher resonances, and ATLAS observes that the values of the plateau are somewhat large, but compatible, with the values of the ratios of the wavefunction at the origin as expected for the color singlet contribution.

## 4.2 Polarization of $\Upsilon(nS)$

The angular distribution of the two leptons from the decay of a vector state can be written as a function of the angles of the outgoing leptons with respect to a given frame where the polar angle  $\theta$  is along the quantization axis,  $W(\theta, \phi) \propto (1 + \lambda_\theta \cos \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi)$  and the parameter  $\lambda_\theta$  is 0 or 1 for 100% longitudinal or transverse polarization.

The reference frames adopted in the literature are more than one: the most used are the Collins-Soper frame, where the quantization axis is chosen as the bisector of the beam directions in the  $\Upsilon$  frame, and the helicity frame, where the quantization axis is chosen along the  $\Upsilon$  direction in the collision center of mass frame. It must be noted that the two definitions are not equivalent (106). It is also possible to express the polarization in terms of frame-independent quantities (107).

The  $\Upsilon(nS)$  from color singlet are expected to be produced with longitudinal polarization (108), while NRQCD, where color octet contributions are significant, predicts a strong transverse polarization for quarkonia produced at high  $p_t$  (109).

The CDF (101,110) and D0 experiments (102) measured the  $\Upsilon(1S)$  polarization in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV, obtaining results that do not agree between the two experiments and are also in disagreement with NRQCD predictions.

The CMS experiment has recently presented a new measurement of  $\Upsilon(3S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(1S)$  angular distribution at  $\sqrt{s} = 7$  TeV in three different quantization frames (111), finding no evidence for either large transverse or large longitudinal polarization.

### 4.3 How much hadronic production proceeds via P-wave states?

The comparison between measurement and theoretical prediction for the total and differential cross sections of any of the bottomonium states requires the knowledge of the fraction of events that originate from the decay of higher bottomonium resonances. This knowledge becomes crucial when measuring the  $\Upsilon(nS)$  polarization, because the angular distribution of  $\Upsilon(nS)$  from  $\chi_{bJ}(1P)$  decays is significantly different.

The first determination of the fraction of  $\Upsilon(1S)$  originating from  $\chi_{bJ}(1P)$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV was presented by CDF (112): for  $p_t > 8$  GeV/c<sup>2</sup> the  $\chi_{bJ}(1P)$  and  $\chi_{bJ}(2P)$  decays account for  $27.1 \pm 6.9 \pm 4.4\%$  and  $10.5 \pm 4.4 \pm 1.4\%$  respectively of the observed  $\Upsilon(1S)$  yield. The fraction of directly produced  $\Upsilon(1S)$ , accounting also for the feed-down from  $\Upsilon(2S)$  and  $\Upsilon(3S)$ , is  $50.9 \pm 8.2 \pm 9.0\%$ .

A new measurement has recently been presented by LHCb (113) in  $pp$  collisions at  $\sqrt{s} = 7$  TeV: for  $6 < p_t < 15$  GeV/c<sup>2</sup> the fraction of  $\Upsilon(1S)$  originating from  $\chi_{bJ}(1P)$  is on average  $20.7 \pm 5.7 \pm 2.1^{+2.7}_{-5.4}\%$ . They do not observe a dependence of this fraction on  $p_T$  in the range studied.

## 5 NEW PHYSICS ASPECTS

Searches for physics beyond the standard model are often the domain of experiments that probe the highest available energies, or, at lower energies, involve the decays of open-flavored heavy mesons like the  $D$ ,  $D_s$ ,  $B$  or  $B_s$ . Heavy quarkonia, however, also may be used to search for hints of new physics. We describe in this section some recent new-physics searches in studies of bottomonium decays.

### 5.1 Decays of $\Upsilon(1S) \rightarrow$ invisible via $\Upsilon(nS) \rightarrow \Upsilon(1S)\pi^+\pi^-$

Decays of  $\Upsilon(nS)$  states to final states that are not observable by typical multipurpose detectors offer an excellent place to search for the impact of physics beyond the standard model, chiefly because the only allowed “invisible” decays of  $\Upsilon(nS)$  within the standard model are the decays  $\Upsilon(nS) \rightarrow \nu\bar{\nu}$ , whose branching fractions can be fairly tightly constrained by the well-measured leptonic decays of  $\Upsilon(nS)$ . The SM prediction for  $\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible})$ , based on the present measurement of the leptonic decay rate of  $\Upsilon(1S)$ , is  $\approx 1 \times 10^{-5}$  (114). If the rate of invisible decays of  $\Upsilon(nS)$  is observed to be substantially larger than the predicted rate, the presence of additional new mediating bosons, which would increase the expected  $\Upsilon(nS) \rightarrow \nu\bar{\nu}$  rate, could be the cause. Another potential explanation would involve the decay of  $\Upsilon(nS)$  to pairs of dark matter candidate particles — such an enhancement could increase the invisible branching fraction up to near  $10^{-3}$  (115).

Recent searches at Belle, CLEO and BABAR for  $\Upsilon(nS)$  to invisible final states have all used a tagging method in which data from collisions at higher  $\Upsilon(nS)$  states are used, and a charged dipion transition to  $\Upsilon(1S)$  is observed. In general, the study of these invisible  $\Upsilon(nS)$  decays depends on the ability of the

detector in question to trigger on very low-multiplicity events, and the suppression of “normal”  $\Upsilon(1S)$  decays to final states which should in principle be detectable.

The first of these searches was published by the Belle Collaboration using  $\pi^+\pi^-$ -tagged  $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  decays taken from a sample of  $11 \times 10^6$   $\Upsilon(3S)$  decays, and yielded a 90% upper limit for the branching fraction  $\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible})$  of 0.25% (116). A similar analysis by the CLEO Collaboration using their sample of  $8.7 \times 10^6$   $\Upsilon(2S)$  decays yielded a somewhat larger upper limit of 0.39% (117). The best upper limit for this branching fraction comes from the BABAR Collaboration, and uses their very large data sample of  $91 \times 10^6$   $\Upsilon(3S)$  decays, lowering the upper limit by an order of magnitude, to  $3.0 \times 10^{-4}$  at 90% confidence (118). Despite the improvement, this limit is still somewhat more than an order of magnitude above the SM prediction.

## 5.2 Search for $\Upsilon(1S) \rightarrow \gamma + \text{invisible}$

In addition to the searches for purely invisible final states arising from  $\Upsilon(1S)$  decay, the BABAR Collaboration published a study of  $\Upsilon(1S)$  decays to a single photon plus a particle which decays to a two-body invisible final state,  $\Upsilon(1S) \rightarrow \gamma A^0; A^0 \rightarrow \chi\chi$  (119). The  $\Upsilon(1S)$  in this study are tagged in a similar manner to those discussed above, although in this case the analysis used a sample of  $98.3 \times 10^6$  events. The final state is then tagged by the observation of a single photon. The search obtained no significant yield of events above the expected background, yielding 90% confidence upper limits on the product branching fraction for scalar  $A^0$ :  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \text{invisible}) < 1.9 - 37 \times 10^{-6}$  for  $M(A^0) < 9.2 \text{ GeV}/c^2$ .

### 5.3 Decays $\Upsilon(nS) \rightarrow \tau^+\tau^-$ and tests of lepton universality

The  $\Upsilon(nS)$  states can decay by  $b\bar{b}$  annihilation to a virtual photon which then will materialize to anything kinematically permitted, e.g., the lepton pairs  $e^+e^-$ ,  $\mu^+\mu^-$ , and  $\tau^+\tau^-$ . Lepton universality predicts equal rates for these three processes; phase space corrections are small. Scalar or pseudoscalar intermediate states in the direct channel, such as light Higgs bosons, will modify these predictions, as their couplings to the leptons will be proportional to the lepton mass. Possible mixing of the  $\eta_b(nS)$  states with light mass Higgs can also impact the relative branching fractions of  $\Upsilon(nS) \rightarrow \ell^+\ell^-$ , since for  $M(A^0)$  above about 9.4 GeV/ $c^2$ , the dominant leptonic decay mode of  $A^0$  is expected to be  $\tau^+\tau^-$ , and  $A^0$  may mediate the process  $\Upsilon(1S) \rightarrow \gamma\eta_b(1S)$ ;  $\eta_b(1S) \rightarrow A^0 \rightarrow \tau^+\tau^-$  (120, 121).

CLEO measured the ratios  $\mathcal{R}_{\tau\tau}^{nS} \equiv \mathcal{B}(\Upsilon(nS) \rightarrow \tau\tau)/\mathcal{B}(\Upsilon(nS) \rightarrow \mu\mu)$  for the  $n = 1, 2, 3$  states with the results shown in Table 5 (122). No deviation was seen from lepton universality at the few percent level.

The BABAR Collaboration has searched for violations of lepton universality in  $\Upsilon(1S)$  decay using their data sample of  $121 \times 10^6$   $\Upsilon(3S)$  decays (121). The analysis determines the ratio of branching fractions,  $\frac{\mathcal{B}(\Upsilon(1S) \rightarrow \tau^+\tau^-)}{\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)}$  in the  $\Upsilon(1S)$  sample provided by  $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  decays. One may “tag” the presence of the  $\Upsilon(1S)$  in these transitions without reconstructing by using four-momentum conservation. That is, if the  $\pi^+\pi^-$  are recoiling against a daughter  $\Upsilon(1S)$ , the recoil mass  $M_{\text{rec}}^2 \equiv (M_{\text{recoil}}^2(\pi^+\pi^-) = s + M_{\pi^+\pi^-}^2 - 2\sqrt{s}E_{\pi^+\pi^-}^*)$  will peak at  $M(\Upsilon(1S))$ . By selecting  $M_{\text{rec}}$  near  $M(\Upsilon(1S))$ , the other final-state particles, which must originate from the decay of  $\Upsilon(1S)$ , may then be studied.

In this analysis, a final state containing exactly four charged tracks was required:  $\Upsilon(1S) \rightarrow \mu^+\mu^-$  was identified by requiring positive muon identifica-

tion for the tracks and a total reconstructed energy consistent with the initial state; the decay  $\Upsilon(1S) \rightarrow \tau^+\tau^-$  was identified using only single-prong decays of  $\tau$ . From the yields, trigger, analysis and reconstruction efficiencies, the ratio  $\frac{\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)}{\mathcal{B}(\Upsilon(1S) \rightarrow \tau^+\tau^-)} = 1.005 \pm 0.013 \pm 0.022$  was obtained. Hence no significant deviation of this ratio from the expected SM value of 0.992 was observed. This marks a substantial improvement in precision with respect to the previous CLEO measurement, and excludes an  $A^0$  with mass lower than 9 GeV/ $c^2$  at the 90% confidence level.

#### 5.4 Search for charged lepton flavor violation in $\Upsilon(nS)$ decays

Another venue for the possible observation of new physics in bottomonium decay is the decay of vector bottomonia to lepton pairs that violate lepton flavor (e.g.,  $\Upsilon(nS) \rightarrow e^+\mu^-$ ). While lepton flavor violation is now well established in the neutrino sector due to oscillations between neutrino flavors, it is generally agreed that lepton flavor violation in the charged sector (CLFV) is so highly suppressed that its observation at any level is an unambiguous sign of new physics. A number of efforts to observe CLFV have been made in  $B$  and  $K$  decays, or in decays of leptons themselves — but the study of charged lepton flavor violating decays of  $\Upsilon(nS)$  has only recently been explored in any detail. Both CLEO (123) (using data at  $\Upsilon(nS)$  with  $n = 1, 2, 3$ ) and BABAR (124) (only  $n = 2$  and 3) have studied decays of  $\Upsilon(nS)$  that violate lepton flavor. In the case of the CLEO analysis, the  $\tau$  lepton was identified in its decay to  $\nu_\tau \bar{\nu}_e e$  while the BABAR analysis used both leptonic and several hadronic  $\tau$  decays. 90% CL upper limits for the branching fractions for CLFV modes of all  $\Upsilon(nS)$  states are below  $10 \times 10^{-6}$ , implying lower limits for the mass associated with CLFV operators of order 1 TeV (124).



### 5.5 Searches for low-mass Higgs in $\Upsilon(\text{nS})$ decays

Frank Wilczek wrote one of the first papers concerning the appearance of new physics in heavy quarkonium decays (125) soon after the the announcement of the first observations of bottomonium at Fermilab, in which he calculated the ratio of the rate of the decay of heavy vectors  $V$  to Higgs +  $\gamma$  to the rate to  $\mu^+\mu^-$ :

$$\frac{\Gamma(V \rightarrow H\gamma)}{\Gamma(V \rightarrow \mu^+\mu^-)} = \frac{G_F m_q^2}{\sqrt{2}\pi\alpha} \left(1 - \frac{m_H^2}{m_V^2}\right)^{1/2}. \quad (4)$$

Under several extensions of the standard model, including the next-to-minimal supersymmetric standard model (NMSSM) (126, 127, 128, 129), the existence of light Higgs bosons is postulated. In particular the NMSSM can have a CP-odd neutral Higgs boson with mass less than 10 GeV/ $c^2$ , making it observable in radiative decays  $\Upsilon(\text{nS}) \rightarrow \gamma A^0$ . Predictions for the branching fractions for such decays are as large as  $10^{-4}$  (127). The most recent searches for CP-odd light Higgs bosons in  $\Upsilon(\text{nS})$  radiative decay have been performed at CLEO and BABAR .

CLEO undertook a study of  $\Upsilon(1S) \rightarrow \gamma + (\mu^+\mu^-, \tau^+\tau^-)$  based on  $21.5 \times 10^4 \Upsilon(1S)$  decays, in which full reconstruction of the  $\gamma\mu^+\mu^-$  final state was attempted, while  $\gamma\tau^+\tau^-$  events were selected based on events having a large missing energy and at least one well-identified  $\mu$  or  $e$  in addition to a well-reconstructed  $\gamma$ . The 90% confidence limits on the product branching fraction  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0; A^0 \rightarrow \ell^+\ell^-)$  for  $\ell^+\ell^- = (\mu^+\mu^-, \tau^+\tau^-)$  were then calculated to range from  $(1 - 20) \times 10^{-6}$  ( $(1 - 48) \times 10^{-5}$ ) for  $A^0 \rightarrow \mu^+\mu^-$  ( $\tau^+\tau^-$ ) with  $A^0$  masses in the range  $M(A^0) < 3.6 \text{ GeV}/c^2$  ( $2M_\tau < M(A^0) < 9.5 \text{ GeV}/c^2$ ). The  $\tau^+\tau^-$  results improved previous limits from ARGUS by more than two orders of magnitude, and remain the most stringent constraints on NMSSM models from this  $A^0$  decay mode.

BABAR has searched for light Higgs bosons in several visible decay modes (130, 131,132,133) in addition to the searches in invisible modes previously discussed (119). The searches for  $A^0 \rightarrow \mu^+\mu^-$  at  $\Upsilon(nS)$  with  $n = 1, 2, 3$  required full reconstruction of the final state, namely a well reconstructed photon in addition to two well-identified muons. Using data samples of  $99 \times 10^6 \Upsilon(2S)$  and  $122 \times 10^6 \Upsilon(3S)$  decays, seeing no evidence for the decay of  $A^0 \rightarrow \mu^+\mu^-$  in radiative events, BABAR reported 90% upper limits of  $\mathcal{B}(\Upsilon(nS) \rightarrow A^0; A^0 \rightarrow \mu^+\mu^-)$  of  $(0.26 - 8.3) \times 10^{-6}$   $((0.27 - 5.5) \times 10^{-6})$  for  $n = 2$  ( $n = 3$ ), and for masses of  $A^0$  ranging from  $2M_\mu$  to  $9.3 \text{ GeV}/c^2$  (130). BABAR also searched for  $A^0$  in  $\Upsilon(1S)$  radiative decay using  $\pi^+\pi^-$ -tagged  $\Upsilon(1S)$  mesons in  $\Upsilon(2S)(\Upsilon(3S))$  data samples containing  $92.8 \times 10^6$  ( $116.8 \times 10^6$ ) events, and set 90% confidence product branching fraction limits of  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0; A^0 \rightarrow \mu^+\mu^-)$  of  $(0.28 - 9.7) \times 10^{-6}$  for  $A^0$  with masses ranging from  $2M_\mu$  to  $9.2 \text{ GeV}/c^2$  (131).

BABAR also performed searches for  $A^0$  in radiative  $\Upsilon(3S)$  decays in which the  $A^0$  decays to  $\tau^+\tau^-$ , with both  $\tau$  required to decay leptonically. The event selection required events to have exactly two charged tracks, identified as either  $e$  or  $\mu$ , and a signal photon with energy greater than 100 MeV. The range of  $A^0$  masses tested was  $(4.03 - 10.10) \text{ GeV}/c^2$ , with a small range of exclusion from  $(9.52-9.61) \text{ GeV}/c^2$  to avoid peaking background due to two-photon cascades from  $\Upsilon(3S)$  through  $\chi_{bJ}(2P)$ . No evidence for  $A^0 \rightarrow \tau^+\tau^-$  was observed, and upper limits of  $\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0; A^0 \rightarrow \tau^+\tau^-)$  of  $(1.5 - 16) \times 10^{-5}$  were set.

## 6 CONCLUSIONS

Since the discovery of the first bottomonium state in 1977, our understanding of the  $b\bar{b}$  system has made steady progress. Comparison of the bottomonium

and charmonium spectra provided strong evidence for the flavor-independence of the strong force. The bottomonium spectrum was surprisingly well described by non-relativistic quantum mechanics, with relativistic embellishments accounting reasonably well (though not perfectly) for fine and hyperfine structure. Significant advances were made by lattice QCD once light-quark degrees of freedom could be taken into account. Above  $B\bar{B}$  threshold, new states  $Z_b(10610)$  and  $Z_b(10650)$  were seen which could be interpreted as  $B\bar{B}^* + \text{c.c.}$  and  $B^*\bar{B}^*$  molecules.

Transitions of bottomonium have continued to be understood in greater and greater detail over the years. Electric dipole transitions were qualitatively predicted in the non-relativistic approximation, with small corrections serving to distinguish among relativistic schemes. Such transitions led to the discovery of the first D-wave bottomonium state, the  $\Upsilon(3D_2)$  (where the spin  $J = 2$  is the most probable). Forbidden magnetic dipole transitions, whose magnitude was difficult to anticipate, provided gateways to the  $\eta_b(1S)$ , while that state and the  $\eta_b(2S)$  were seen in electric dipole transitions from the  $h_b(1P)$  and  $h_b(2P)$ . In turn, the  $h_b(1P)$  (first discovered in the decay  $\Upsilon(3S) \rightarrow \pi^0 h_b(1P)$ ) and  $h_b(2P)$  were seen in the surprisingly strong transitions  $\Upsilon(5S) \rightarrow \pi^+\pi^- h_b([1, 2]P)$ , via the gateways of  $Z(10610)$  and  $Z(10650)$ .

Information on quarkonium production has helped to understand the subtleties and limitations of perturbative and nonperturbative QCD. A key issue, still unresolved, is the role of color-octet pairs in the  $Q\bar{Q}$  wavefunction. Descriptions of production cross sections seem to be only marginally improved with their inclusion, and the jury is still out regarding their role in hadronic quarkonium decay. Details still under study include the dependence of production cross sections on transverse momentum  $p_T$  and rapidity  $y$ , the polarization of hadronically pro-

duced  $\Upsilon$  states (found to be small), and the role of feed-down from hadronically produced  $\chi_b$  states, accounting for several tens of percent of the hadronically produced  $\Upsilon$  levels.

The study of bottomonium production in inclusive hadronic interaction is about to enter an era of precision measurements: The LHC experiments will have the opportunity to measure the direct cross sections and polarization, disentangling the contribution of higher resonances.

Finally, thanks to recent contributions from CLEO and BABAR over the past several years in their studies of bottomonium decays, additional constraints on new physics have been determined. These experiments have searched for hints of new physics in the direct decays of  $\Upsilon(1S)$  to invisible final states, constraining the overall branching fraction to such final states to be less than  $3 \times 10^{-4}$ , and additionally the decays of  $\Upsilon(1S)$  to a radiative photon plus an invisible final state, whereby limits on the product branching fractions  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \text{invisible})$  were set for a wide range of masses of light mass Higgs candidates  $A^0$ .

Light mass Higgs bosons have also been studied in radiative decays of  $\Upsilon(nS)$  states, where the  $A^0$  decays leptonically. Relatively stringent limits for  $A^0$  between  $2M_\mu$  down to as low as few parts in  $10^7$  (and up to approximately  $1 \times 10^5$ ) were set on the product branching fractions  $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \mu^+ \mu^-)$ . Somewhat higher limits for decays to  $\tau^+ \tau^-$  were obtained (a few times  $10^{-5}$ ).

Leptonic decays of  $\Upsilon(nS)$  also prove to be a testing ground for new physics. CLEO and BABAR have done extensive studies of their large  $\Upsilon(nS)$  data sets for violations of lepton universality or of lepton number, both of which would require new physics to explain.

We look forward to many further insights on QCD and on new physics signa-

tures from the study of the rich bottomonium system, from experiments already completed (BABAR, Belle, CDF, D0) and from those in progress or planned (LHCb, ATLAS, CMS, Belle II, ...). Bottomonium has truly been an ideal laboratory in which to study known interactions and search for new ones.

## ACKNOWLEDGMENTS

The work of J.L.R. was supported in part by the U.S. Department of Energy through Grant No. DE-FG02-90ER40560. The Work of T.K.P. was supported in part by the National Science Foundation through Grant No. PHY-1205843.

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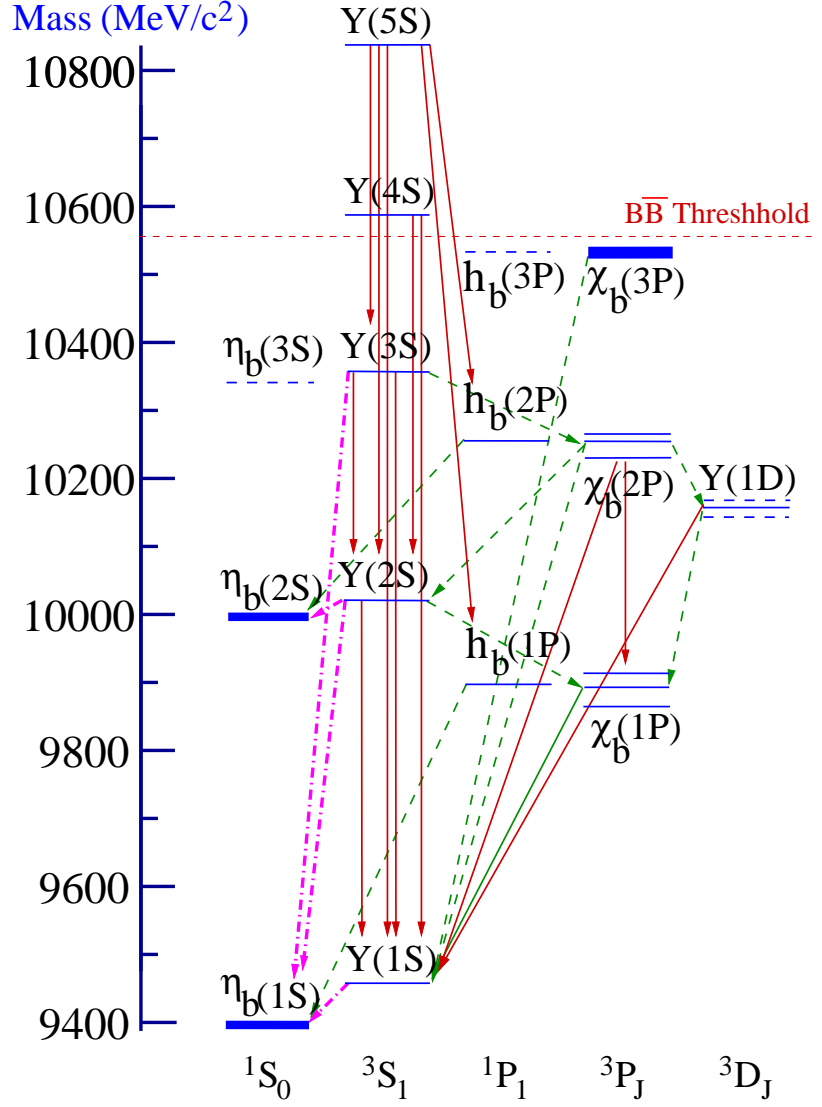


Figure 1: Current knowledge of the bottomonium system. Solid lines correspond to known states while dashed lines are predicted ones. The thicker lines indicate the range of measured masses for newly discovered states. (Solid, dashed, dot-dashed) arrows denote (hadronic, electric dipole [E1], and magnetic dipole [M1]) transitions, respectively.

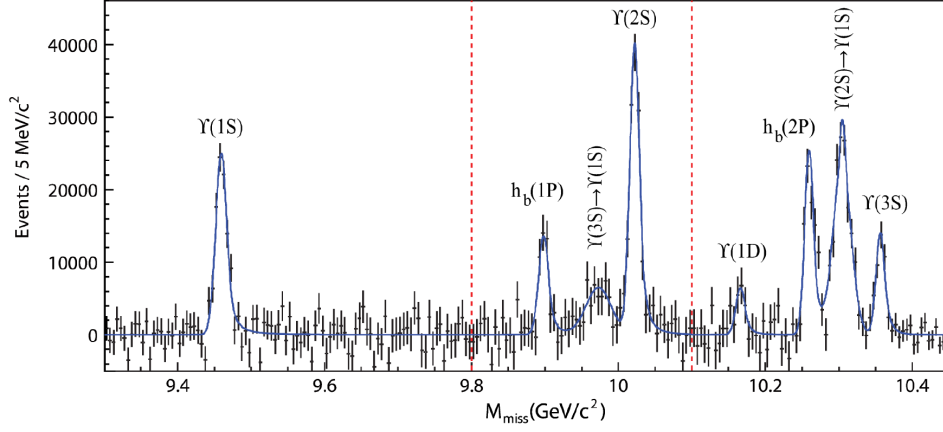


Figure 2: Recoil mass spectrum against The  $\pi^+\pi^-$  recoil mass spectrum from Belle (28). In the figure, the peaks in the recoil mass spectrum arise from  $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(nS)$  with  $n = 1, 2, 3$ , ( $\Upsilon(3S), \Upsilon(2S)) \rightarrow \pi^+\pi^-\Upsilon(1S)$  arising from  $\Upsilon(3S)$  and  $\Upsilon(2S)$  produced via ISR, and direct  $\Upsilon(5S) \rightarrow \pi^+\pi^-(h_b(1P), h_b(2P))$ . The peak near  $10.16 \text{ GeV}/c^2$  constitutes evidence for  $\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1D)$ .

Table 1: Properties of candidates for molecular bottomonium.

State	Mass	Width
	( $\text{MeV}/c^2$ )	(MeV)
$Z_b(10610)$	$10608.4 \pm 2.0$	$15.6 \pm 2.5$
$Z_b(10650)$	$10653.2 \pm 1.5$	$14.4 \pm 3.2$

Table 2: Comparison of measurements of forbidden M1 transitions  $\Upsilon(nS) \rightarrow \eta_b(1S)$ .

Initial $\Upsilon$	BABAR		CLEO (19)	
	2S (73)	3S (18)	2S	3S
$N(\Upsilon) (10^6)$	91.6	$109 \pm 1$	$9.32 \pm 0.19$	$5.88 \pm 0.12$
$M[\eta_b(1S)] (\text{MeV}/c^2)$	$9394.2^{+4.8}_{-2.3} \pm 2.0$	$9388.9^{+3.1}_{-2.3} \pm 2.7$	–	$9391.8 \pm 6.6 \pm 2.0$
$\mathcal{B}[\gamma\eta_b(1S)] (10^{-4})$	$3.9 \pm 1.0^{+1.1}_{-0.9}$	$4.8 \pm 0.5 \pm 0.6$ (a)	$< 8.4$	$7.1 \pm 1.8 \pm 1.3$
$\Gamma(\eta_b(1S) (\text{MeV}/c^2)$	(b)	10 (c)	$10 \pm 5$ (c)	$10 \pm 5$ (c)

(a) Updated systematic error in (73). (b) Consistent with being dominated by resolution of  $18 \text{ MeV}/c^2$ . (c) Assumed.

Table 3: Branching fractions and upper limits (in units of  $10^{-4}$ ) for hadronic transitions between  $\Upsilon(nS)$  levels involving  $\eta$  and  $\pi^0$  emission.

		CLEO (84)	BABAR (82)	Belle (85)
$\Upsilon(2S)$	$N(\Upsilon) (10^6)$	$9.32 \pm 0.14$	$98.6 \pm 0.9$	$158 \pm 4$
	$\rightarrow \eta\Upsilon(1S)$	$2.1^{+0.7}_{-0.6} \pm 0.3$	$2.39 \pm 0.31 \pm 0.14$	$3.57 \pm 0.25 \pm 0.21$
	$\rightarrow \pi^0\Upsilon(1S)$	$< 1.8$	–	0.41
$\Upsilon(3S)$	$N(\Upsilon) (10^6)$	$5.88 \pm 0.10$	$121.8 \pm 1.2$	–
	$\rightarrow \eta\Upsilon(1S)$	$< 1.8$	$< 1.0$	–
	$\rightarrow \pi^0\Upsilon(1S)$	$< 0.7$	–	–
	$\rightarrow \pi^0\Upsilon(2S)$	$< 5.1$	–	–

Table 4: Comparison of measurements of  $\Upsilon(mS) \rightarrow \pi^+\pi^-\Upsilon(nS)$  transitions, where  $m \in (2, 5)$  and  $n \in (1, 3)$ .

Process	$\Gamma_{total}$	$\Gamma_{\pi^+\pi^-\Upsilon(nS)}$	Reference
	MeV	keV	
$\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	0.032	6.0	(63)
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	0.020	0.9	(63)
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(2S)$	0.032	0.6	(63)
$\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	20.5	1.8	(63)
$\Upsilon(4S) \rightarrow \pi^+\pi^-\Upsilon(2S)$	20.5	1.7	(63)
$\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(1S)$	110	590	(41)
$\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(2S)$	110	850	(41)
$\Upsilon(5S) \rightarrow \pi^+\pi^-\Upsilon(3S)$	110	520	(41)

Table 5: Ratios  $\mathcal{R}_{\tau\tau}^{nS}$  of  $\Upsilon(nS)$  branching fractions to  $\tau^+\tau^-$  and  $\mu^+\mu^-$  and inferred branching fractions of  $\Upsilon(nS)$  to  $\tau^+\tau^-$  (122, 121).

	$\mathcal{R}_{\tau\tau}^{nS}$	$\mathcal{B}(\Upsilon(nS) \rightarrow \tau^+\tau^-)$ (%)	Reference
$\Upsilon(1S)$	$1.02 \pm 0.02 \pm 0.05$	$2.54 \pm 0.04 \pm 0.12$	(122)
$\Upsilon(1S)$	$1.005 \pm 0.013 \pm 0.022$	$2.49 \pm 0.03 \pm 0.07$	(121)
$\Upsilon(2S)$	$1.04 \pm 0.04 \pm 0.05$	$2.11 \pm 0.07 \pm 0.13$	(122)
$\Upsilon(3S)$	$1.08 \pm 0.08 \pm 0.05$	$2.52 \pm 0.19 \pm 0.15$	(121)